Electronic Current Flow Through Ideal Dielectric Films*

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1 Introduction

During the past few decades, a large literature has accumulated on the subject of current flow through dielectric films. Much of this material contains detailed analyses of many physical effects and a great deal of multi-parameter curve fitting. Until recently, all this activity had given the field a rather bad name, since it appeared that all effects were very complicated and nothing could be understood in a first-principles way. It is true, in fact, that in many thin-film systems, the current flow is dominated by impurities, trapping processes, and so on, so that no simple, clear picture emerges for the mechanism of current flow. However, in the past few years it has become clear that certain insulating materials behave in a nearly ideal fashion, and can be understood in a very simple and fundamental way.

In this chapter, I shall not attempt to discuss the mass of literature dealing with data on dielectrics that were not well-characterized and well-understood. Instead, I shall concentrate on examples in which nearly ideal behavior was observed, and in which the simple physics of the current-flow processes is clear. In retrospect, it seems obvious that much of the previous data is also understandable on rather simple grounds, and that there were a number of conceptual errors that led to the belief that vastly complicated processes were involved. This is by no means true for all the data in the literature, but certainly with good hindsight resulting from a clear understanding of ideal materials, a much better understanding of the non-ideal cases is also possible. Since the details of all the results I shall cite are available in the published literature, I shall discuss only the ideas and basic principles involved, and give references where a more complete discussion may be found.

2 The Metal-Vacuum Interface

Electronic states in a metal are filled up to some maximum energy, the Fermi level. Electrons in vacuum have a certain minimum energy: the rest energy in vacuum, or "vacuum level." Both of these energies are usually discussed in terms of some arbitrary reference energy. As long as one is working in a homogeneous medium (either metal everywhere or vacuum everywhere), the reference energy does not matter. However, when we discuss the interface between the metal and the vacuum, we must use the same reference energy for electrons in the metal and for electrons in the vacuum. In other words, we must know how the energies in the metal, and in particular the Fermi energy, are related to the energy of an electron in vacuum. In terms of an energy diagram, we need to know at what position to draw the vacuum level relative to the

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Fermi level in the metal. The various metals have very different electron energies, and one might expect that for certain metals the Fermi level would lie above the vacuum level, and for others the Fermi level would lie below the vacuum level. However, what is actually found is that for all known metals, the Fermi level lies below the vacuum level; that is, it requires energy to remove an electron from any metal and take it into vacuum. There is a very simple experiment we can do to convince ourselves that this is in fact the case. Suppose we place two metal plates facing each other in a vacuum, as shown in Fig. 1, and apply a voltage between the two metal plates with an ammeter connected so that we can measure how much current flows between the metal plates through the vacuum. If the Fermi level in the left-hand (negative) plate were higher than the vacuum level, electrons would spontaneously spill out into the vacuum and be carried across by the electric field to the positive plate, and we would find that we could draw a large current through the vacuum. In fact, when we do the experiment we find that, no matter which metal we use, at room temperature essentially no current flows through the vacuum. It is often said that vacuum is an excellent insulator. That really is not a statement about vacuum at all, but rather about the energy barrier between the Fermi level of the metal and the vacuum level. With this information, we can draw an energy diagram of the metal-vacuum interface as shown in Fig. 2.

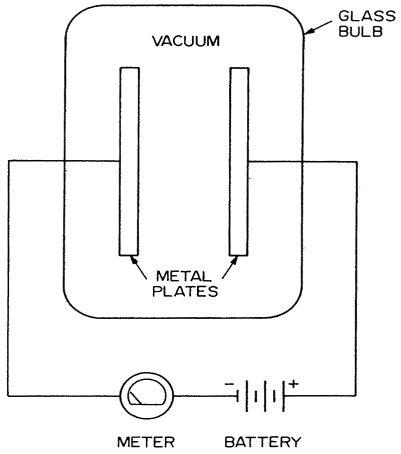

Figure 1: Schematic of experiment to determine the energy of electrons in metal relative to vacuum.

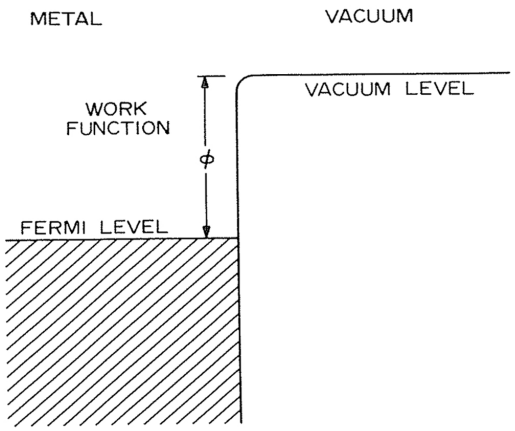

Figure 2: Relative energies of electrons in metal and in vacuum.

The difference in energy between the Fermi level in the metal and the vacuum level is just the well-known work function ϕ of the metal. It is the amount of work necessary to get an electron from the Fermi level of the metal out into the vacuum. At very low temperatures, electrons in the metal have insufficient energy to surmount the barrier and make their way out of the metal into the vacuum. However, as the temperature of the metal is raised, more and more electrons are evaporated into the vacuum.

Thus, if we take the experiment of Fig. 1 and heat the plate on the left, we find that, as the temperature is raised, the amount of current we can draw through the vacuum becomes larger and larger. We can illustrate this situation on an energy diagram, as shown in Fig. 3. Two identical metal plates are shown

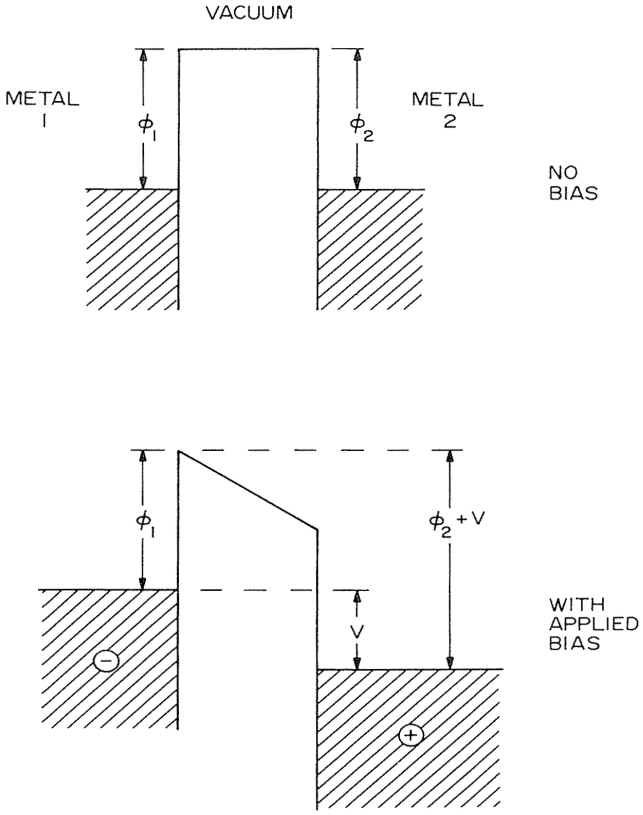

Figure 3: Energy diagram of the experiment of Fig. 1, showing the conditions with and without applied bias.

facing each other, each with a work function and the vacuum level shown between. If there is no voltage applied between the metal plates, the vacuum level is horizontal; that is, the energy of an electron at rest in the vacuum is independent of its position between the two metals. However, if we apply a voltage by connecting a battery between the two metal plates, the energy of electrons in the negative (left) plate is raised relative to those of the positive metal. Any electrons that are now liberated from the negative plate will be accelerated toward the positive plate until they smash into it and lose their energy by collisions with the other electrons and atoms in the metal. The current that can flow in this situation is governed by how many electrons in metal 1 have enough energy to surmount the work-function barrier ϕ_1. Once they have overcome this obstacle, they are drawn across through the vacuum by the electric field into metal 2. Electrons in metal 2 are also evaporated out into the vacuum. However, they must not only surmount the work-function barrier, but in addition climb uphill against the electric field until they make their way over the top and arrive at metal 1. This, of course, requires a great deal more energy. In fact, the amount of energy required over and above the work function of metal 2 is just the applied voltage V. If there are electrons in metal 2 with enough energy to not only surmount the work function ϕ_2 but also

the potential barrier created by the battery, they must have energy $\phi_2 + \mathrm{V}$.

For energies well above the Fermi level, the energy distribution of electrons in a metal follows the Boltzmann law

$$\mathrm{N} \propto \exp\left(-\frac{\mathrm{E}}{\mathrm{kT}}\right), \tag{1}$$

where N is the density of electrons at any given energy, T is the absolute temperature, and k is the Boltzmann constant. The energy E of the electrons is measured from the Fermi level. Thus, if the applied voltage is more than a few kT, the current from right to left will be small compared with the current from left to right, since very few electrons will have the energy to overcome both the work function and the applied voltage. In this case, the current will be given very nearly by

$$\mathrm{J} = \mathrm{J}_0 \exp\left(-\frac{\phi_1}{\mathrm{kT}}\right). \tag{2}$$

3 Current-Voltage Characteristic of the Thermionic Diode

So far, we have been discussing the symmetrical situation in which the work functions of both metals were equal. In such a situation, the current for either direction of applied bias will saturate at the value given by Eq. 2. In more practical situations, the work functions of the two metals may be quite different. Let us consider the practical device[1] shown in Fig. 4. The structure contains a barium-coated oxide cathode with work function ϕ_1 and a titanium anode with work function ϕ_2. We shall operate the device at elevated temperatures, so that electrons may be emitted from the barium cathode, which we shall make negative with respect to the high-work-function titanium anode. Under these conditions, we would expect a preponderance of current flow from the low-work-function metal to the high-work-function metal. In fact, by just knowing the Boltzmann law, we can predict how the current that flows through the vacuum should depend on the voltage we apply between the two metals. The energy diagram for the device under

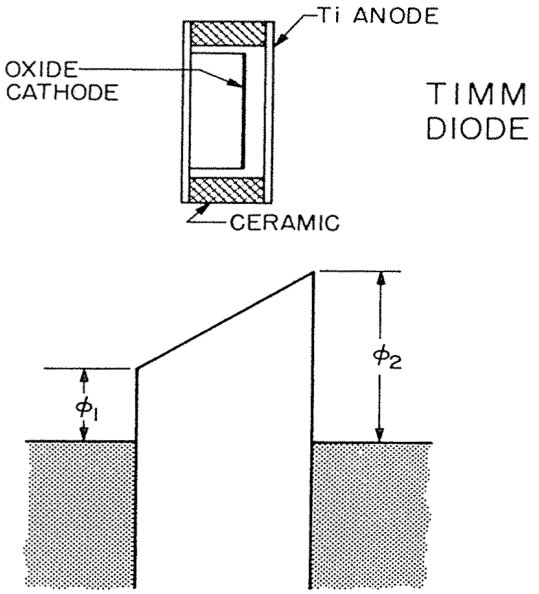

Figure 4: Schematic and energy diagram of practical vacuum diode.

[1]These devices were originally designed to work as part of an integrated vacuum-tube electronic system, and were kindly supplied by the General Electric Company, Owensboro, Kentucky.

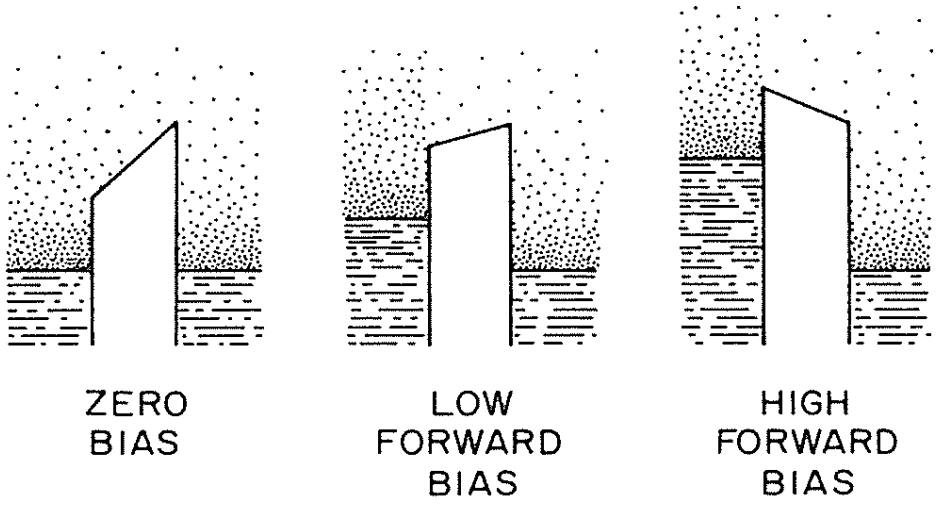

Figure 5: Schematic representation of the Boltzmann distribution of electrons in two metal electrodes of the device of Fig. 4. Note how the application of applied bias shifts one distribution relative to the other and thus causes current flow.

various bias conditions is shown in Fig. 5, together with a schematic representation of the Boltzmann distribution of electrons in the electrodes.

With zero applied bias the device is in equilibrium, and the same number of electrons cross the peak of the barrier from left to right and right to left. As the oxide cathode is made more negative, its electron population is displaced toward higher energies, and a net current flows from left to right. In the low-forward-bias range, the maximum height of the energy barrier that electrons must cross to get from the left to the right is $\phi_2 - \mathrm{V}$. Thus, as the applied voltage is raised, the number of electrons with enough energy to surmount this potential barrier should increase exponentially

$$\mathrm{J} \propto \exp\left(-\frac{\phi_2 - \mathrm{V}}{\mathrm{kT}}\right). \tag{3}$$

Thus, for applied voltages less than the difference between the two work functions, the current through the device will increase exponentially with the applied voltage. When the voltage becomes equal to the difference between the work functions, the height of the potential barrier that the electrons must surmount becomes equal to ϕ_1 and does not decrease with further increase in the applied voltage. Therefore, in high forward bias (voltages greater than $\phi_2 - \phi_1$), the current saturates and does not continue to increase.

Data taken on the actual device running at 470°C are shown in Fig. 6. For potentials less than 2.8 V, the current does in fact increase exponentially and saturates for larger voltages. We have thus determined the difference between the two metal work functions, $\phi_2 - \phi_1 = 2.8$ eV.

In addition, from the slope of the exponential part of the curve, we can determine the temperature of the device (or if we know the temperature of the device, we can check to see whether the Boltzmann law is being obeyed). The line drawn through the experimental points is such that the current increases by a factor of e for every kT increase in the applied voltage, where the temperature T was taken from a thermocouple attached to the device in the oven. It is clear that the current increases in exactly the way predicted by the Boltzmann factor.

We encounter many devices in which the current increases exponentially with the voltage. Most of these operate on the same fundamental principle as the vacuum diode we have just discussed; that is, the height of an energy barrier which thermally excited electrons must surmount depends directly on the voltage

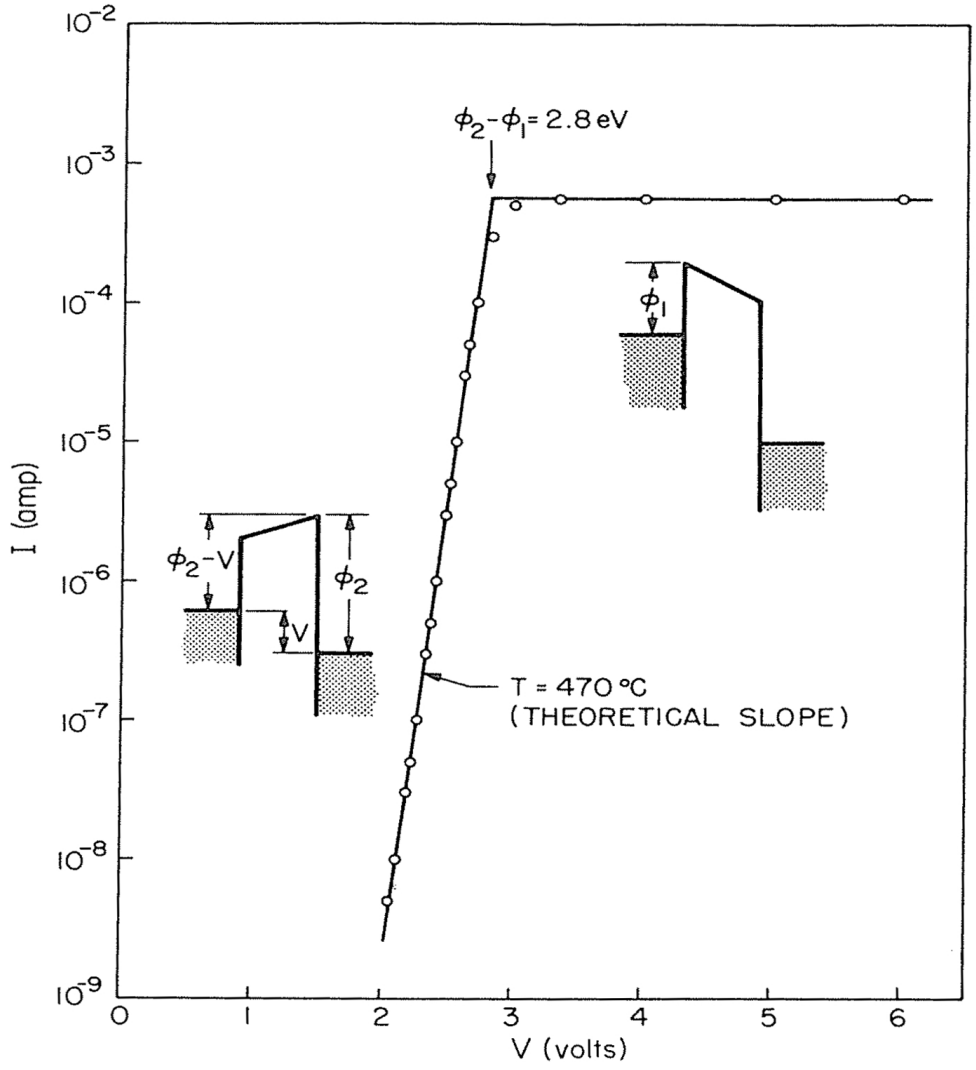

Figure 6: Current-voltage characteristic of the thermionic diode of Fig. 4. The device was run in an oven at 470° C. Note the knee in the slope when the applied bias reaches $\phi_2 - \phi_1$.

applied. In any device in which this situation is found, the current will depend exponentially on the voltage, increasing by a factor of e for every kT increase in the applied bias.

So far we have shown that the current flowing through our vacuum dielectric is thermionic in origin, and we have measured the difference between the two work functions. In order to complete our understanding of the device, we must know the absolute value of either ϕ_1 or ϕ_2.

If we bias the unit just above the knee in the I-V curve (e.g., to 5 V), the current is given by Eq. 2 and we can determine ϕ_1 by varying the temperature of the diode and observing the current. From Eq. 2, we would expect a plot of the logarithm of the current as a function of reciprocal absolute temperatures to be a straight line whose slope is the barrier energy divided by Boltzmann's constant. This thermal-activation-energy plot is a direct way of measuring the energy barrier ϕ_1.

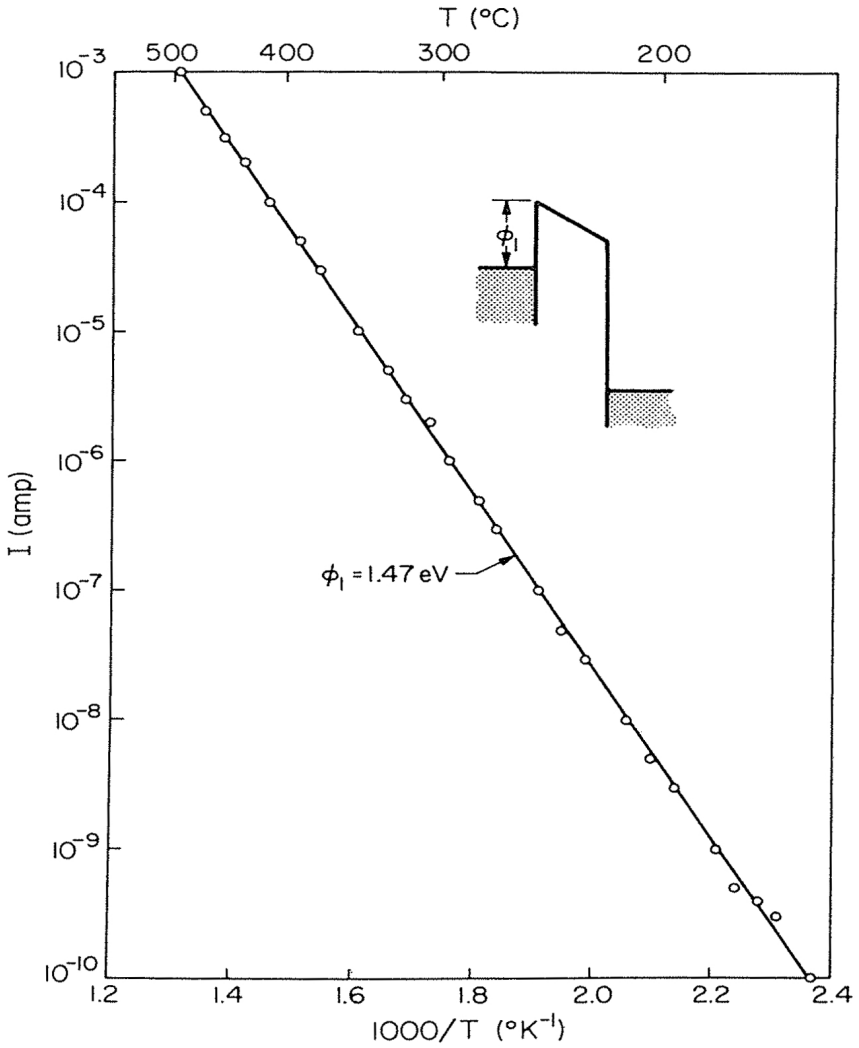

Figure 7: Dependence on temperature of the thermionic current through the device of Fig. 4. The data were taken at an applied voltage of 5 V.

Data taken on the thermionic diode are shown in Fig. 7. We obtain a straight line as expected. The slope of this line gives directly $\phi_1 = 1.47$ eV.

We have now determined all parameters that are important for the operation of the device. The value we infer for the titanium work function is 4.27 eV and can be checked against published values, which range from 3.95 to 4.75 eV. Thus, we have confidence that our energy diagram and concept of current flow are not only internally consistent, but also correct.

4 Thermionic Currents in Thin Insulators

The behavior of a thin insulating film in which the mobility is reasonably high and the density of donors (or acceptors) and traps is low enough for the band bending over the thickness of the film to be negligible, represents a situation conceptually identical with that encountered in the vacuum tube of the preceding section [1].

In principle, the only change is that the work function is replaced by the energy barrier from the Fermi

level of the metal to either the conduction or the valence band of the dielectric, whichever is lower. The study of metal-semiconductor and metal-insulator barriers is a highly-refined topic in its own right and has been reviewed elsewhere [2]. We need here only to recognize that such barriers exist and that they can be measured by a number of well-known techniques.

Although a vast literature exists concerning the electrical behavior of thin insulating films, there has been a persistent problem in the characterization of the film itself. For this reason, quantitative agreement between models similar to that used for the vacuum diode and real measurements on insulating films have only recently been achieved. In this section, we discuss a straightforward approach to obtaining an insulating film that is well-characterized, and in which the requirements for behavior similar to that of a vacuum have been met. One starts with a single crystal of highly pure and well-characterized material for which the carrier concentration, trapping concentration, and barrier energies for various metals are known. This single crystal is then cleaved thin enough to permit making thin-film-type measurements.

This approach has been successfully employed recently by using gallium selenide single crystals with carrier concentrations of less than 10^{15}cm^{-3}. A schematic representation of the crystal structure of gallium selenide is shown in Fig. 8. It will be noted that each layer consists of a highly regular array of gallium

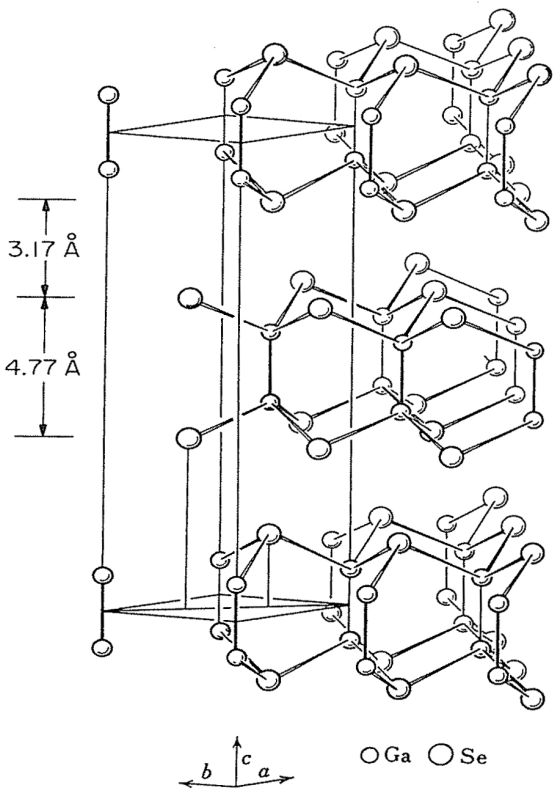

Figure 8: Schematic representation of the crystal structure of gallium selenide. A small section of three layers is illustrated.

and selenium atoms in a simple packing arrangement. Adjacent layers are held together by van der Waals forces, which permits easy cleavage of the crystal into very thin layers. Because of its low carrier concentration, the dielectric constant of the material could be determined from samples of macroscopic thickness [3]. The carrier concentration was then determined from measurements of $1/\text{C}^2$ versus V made on Schottky diodes formed on cleaved surfaces of the bulk crystal. By observing the behavior of the capacitance under incident illumination, an upper limit on the deep-trap concentration could also be set. The total of net carrier concentration and deep-trap concentration for this material was less than

10^{15}cm^{-3}. Therefore, for samples less than 1000 $\mathring{A}$ thick, the band bending under any conceivable bias conditions will be negligible.

Photoemission measurements on the same Schottky barriers give values for the barrier energies relative to the valence band [4]. A plot of the square root of the photo-yield from such an experiment as a function of photon energy is shown in Fig. 9. The intercepts on the hv axis are the barrier energies relative to the

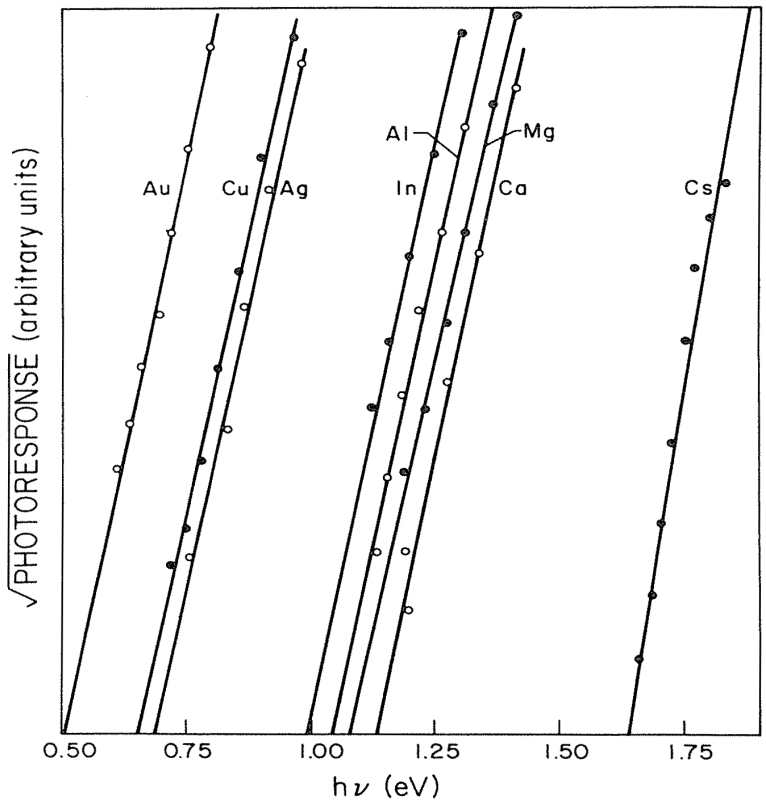

Figure 9: Photoresponse of metal contacts to p-type gallium selenide. The intercepts on the hv axis are the barrier energies; that is, the location of the Fermi level for the particular metal relative to the valence band.

valence band of the gallium selenide. Thin-film samples can be prepared by evaporating aluminum onto one side of a freshly-cleaved gallium selenide flake a few microns in thickness. The metalized side of the sample is then mounted with a conducting epoxy to a metal block and the opposite side of the sample is removed by successive application and removal of ordinary *Scotch Magic Transparent Tape*. With certain rudimentary precautions, this procedure results in rather uniform samples of reasonably large area, with thicknesses in the 50– to 1000 $\mathring{A}$ range. Subsequently, gold dots are evaporated through a fine-mesh mask onto the freshly-peeled surface.

A knowledge of the barrier energies derived from Fig. 9 and the band gap of gallium selenide (2.0 eV) allows us to construct an energy-band diagram for the sample, as shown in Fig. 10. For samples at the upper end of the thickness range, tunneling can be neglected to first order, and a simple thermionic-current-flow process is observed. The current-voltage characteristic of a typical sample 600 $\mathring{A}$ thick is shown in Fig. 11. It is immediately apparent that the qualitative features are similar to those for the thermionic vacuum diode. The current rises exponentially with voltage until the electric field in the device approaches zero and then flattens out. Some quantitative differences from the vacuum diode are also apparent. The rate of increase in the exponential portion of the curve is not quite that expected from Eq. 3. In addition, current above the flat band condition is not totally independent of voltage, but still increases. The same

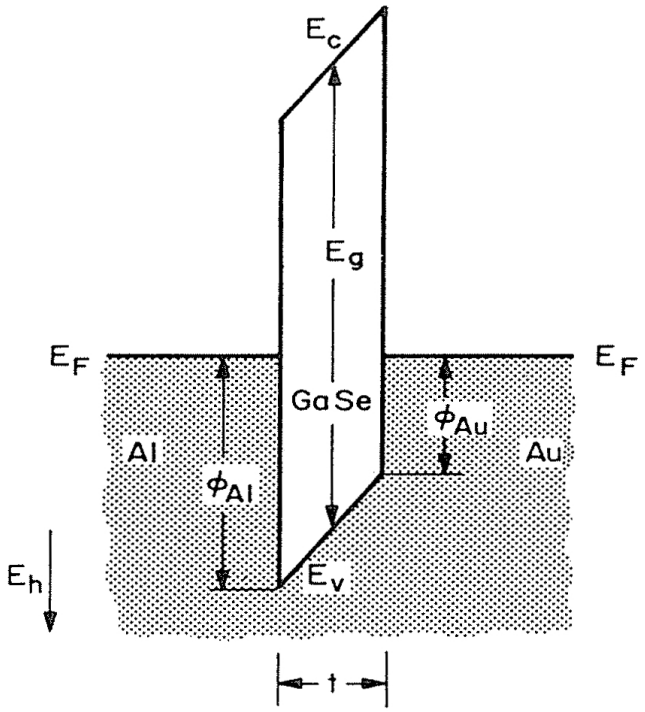

Figure 10: Energy-band diagram for an Au-GaSe-Al structure. The energy gap of gallium selenide is 2.0 eV, ϕ_{Au} is 0.52 eV, and ϕ_{Al} is 1.05 eV (see Fig. 9).

is true for the reverse current of the device. However, the electric fields present in this device are many orders of magnitude larger than in the thermionic vacuum diode, and one would have to know the detailed dependence of the barrier energy on electric field to determine the exact shape of the current-voltage curve. The way in which this has been done to calculate the theoretical curve shown in Fig. 9 is discussed in Ref. [1].

Qualitatively, we expect the device to be operating in precisely the same way as the vacuum diode, and when biased just above the knee of the curve (e.g., +0.75 V applied to the gold electrode), we would expect to measure the barrier energy of the gold electrode directly by observing the dependence of the current flow upon device temperature. The results of this experiment are shown in Fig. 12 and are essentially identical with those for the thermionic vacuum diode except that the barrier energy is only 0.52 eV instead of 1.4 eV.

This, of course, accounts for our ability to perform the experiment at room temperature instead of 470°C, as was necessary with the vacuum diode. A similar measurement can be performed in the reverse direction, which was not possible with vacuum diode because of the very high work function of the titanium anode. The results are shown in Fig. 12. In this case, the experiment gives an energy of approximately 1 eV for the aluminum-gallium selenide barrier. Both of these values are in excellent agreement with the results of photoresponse shown in Fig. 9, and give us confidence in the simple thermionic model of current flow.

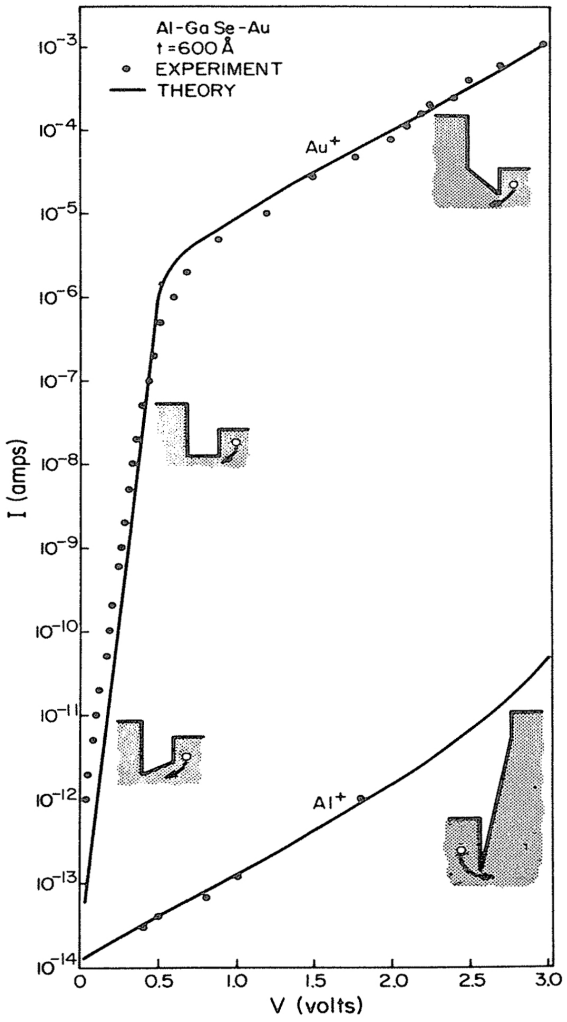

Figure 11: Current-voltage characteristic of an Au-GaSe-Al structure 600 $\mathring{A}$ thick. Insets show the relevant portion of the energy diagram at various biases. As indicated, holes are the dominant current-carrying species.

5 Tunneling Through Thin Insulating Films

So far, we have discussed a mechanism of current flow that involved electrons surmounting a potential barrier caused by the forbidden gap of an insulator. This is not the only mechanism by which current can flow through an insulator. When the insulating film becomes sufficiently thin, it is no longer opaque to electrons. Electrons that pass directly through the forbidden gap without surmounting the barrier are said to "tunnel" through the forbidden gap. This lack of total opaqueness of a forbidden gap of any insulator (including vacuum) is a consequence of the basic quantum mechanical nature of the electron.

The wave function of a free electron in vacuum, ψ, is of the form

$$\psi = \exp(\mathrm{ikx}), \qquad \text{where} \qquad \hbar\mathrm{k} = \sqrt{2\mathrm{mE}}. \tag{4}$$

Here, the electron energy E is measured from the vacuum level. For $\mathrm{E} > 0$, this expression represents a traveling wave in the x direction whose momentum $\hbar$k is proportional to the square root of the electron energy. This result is familiar from elementary mechanics and is contained in the plot of E versus k^2 shown in Fig. 13. A not-so-familiar result is also evident in this figure. For negative values of E, the

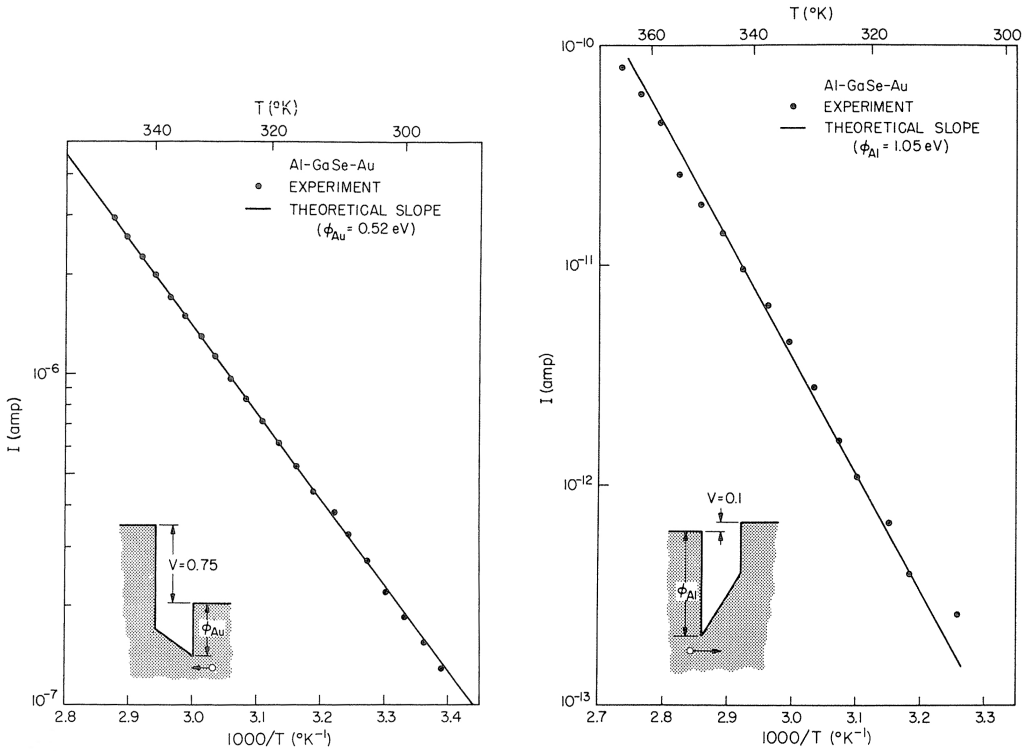

Figure 12: Temperature dependence of the forward (left) and reverse (right) currents in the Au-GaSe-Al structure of Fig. 10.

quantity k^2 is negative, and hence k is imaginary. The electron no longer has propagating solutions, but rather damped ones of the form

$$\psi = \exp(-\mathrm{kx}), \tag{5}$$

where k is now the imaginary part of the wave vector. These "forbidden" damped solutions are not appropriate for an electron in an extended space since they increase without limit for negative x. However, in a finite structure, they are quite appropriate and contain an important fundamental physical fact: it is not possible to confine an electron absolutely. No matter how high a potential barrier we set up, the electron has a finite probability (given by the square of the wave function) of being where it does not have the energy to be.

For metal-vacuum interface like that shown in Fig. 2, it is clear that electrons in the metal cannot stop abruptly at the surface, but in fact penetrate a short distance into the vacuum, the probability P of finding one dying out with increasing x as

$$\mathrm{P} \propto \exp(-2\mathrm{kx}), \tag{6}$$

where now x is measured from the metal surface. Under normal circumstances, the distance $\frac{1}{2k}$ over which probability decreases by a factor of e is less than an angstrom, and hence for practical purposes, the interface is abrupt. However, when two electrodes are very closely spaced (e.g., less than 100 $\mathring{A}$), an electron in one electrode can make a transition to the other electrode through the tail of its damped wave function. The probability of such a transition is just proportional to the probability P of finding an electron from electrode 1 in electrode 2. From Eq. 6

$$\mathrm{P} \propto \exp(-2\mathrm{kt}), \tag{7}$$

where t is the spacing of the electrodes.

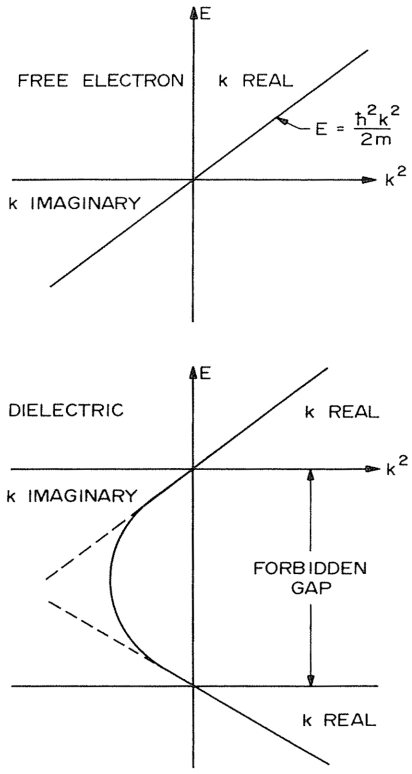

Figure 13: Schematic representation of the dependence on electron energy E of the real and imaginary parts of the wave vector k. Top: free electron. Bottom: electron in a dielectric or semiconductor. Regions of imaginary k correspond to damped wave functions.

For any tunneling path between a filled state in one electrode opposite an empty state in the other, Eq. 7 gives the probability per second that a transition will occur. The tunneling current is just the charge on the electron times the sum of all probabilities (those from left to right taken as positive, and those from right to left as negative). Since the number of filled states in one electrode opposite empty states in the other is proportional to the voltage, we expect the current to be proportional to voltage, and for a small applied bias this is the case.

At higher voltages, however, another effect completely dominates the current-voltage characteristic. Referring to Fig. 14, we see that by applying a bias voltage, we have moved the tunneling path of electrons near the left-electrode Fermi level closer to the vacuum level, where (from Eq. 4) the value of k is lower. Hence, the average k for the entire path is lower, and the tunneling probability will increase in a generally exponential way with bias. Although a detailed analysis can be made (and has been many times in the literature), it is not useful in the study of real dielectrics because the dependence of k on E in these materials never follows the simple form given in Eq. 4. Rather, the value of k must decrease at sufficiently low energies since it must again be zero at the valence-band edge.

The type of dependence expected is shown in Fig. 13. Since k is in the exponent, the k versus E behavior of any material completely dominates the current versus voltage characteristic, and essentially no progress was made toward a quantitative understanding of thin-film tunneling until this fact was recognized and squarely faced. The real question, then, is how to determine the k versus E relationship in any real material in order to calculate the current-voltage characteristics of a metal-dielectric-metal sandwich formed from this material. It will probably come as no surprise to the reader than tunneling itself provides the most sensitive probe with which to determine the nature of the forbidden gap in solids.

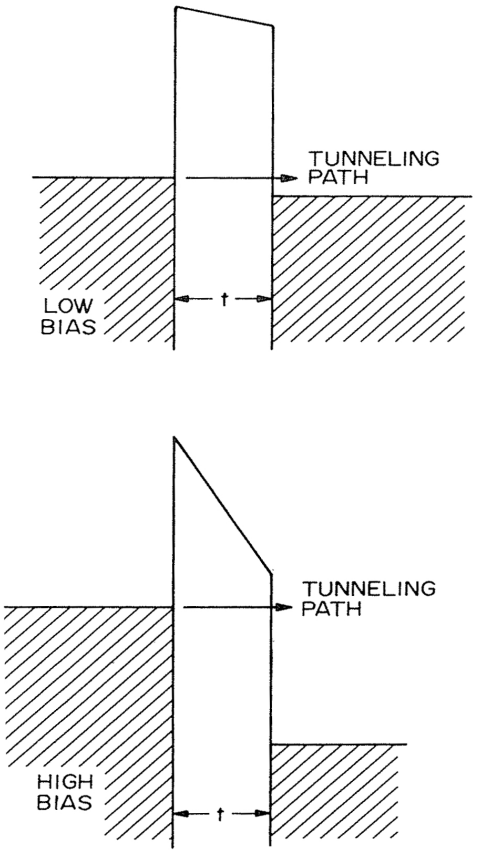

Figure 14: Energy diagram of metal-vacuum-metal structure at low and high applied bias. Note that although the length of the tunneling path is independent of bias voltage for $V < \phi$, the tunneling path at higher bias is nearer the vacuum level and hence the average k is lower.

As a first step, we notice that the reciprocal of the probability per second that an electron will tunnel from one electrode to the other is the relaxation time of this system when a small quantity of charge is taken from one electrode and placed on the other. In electrical engineering terms, this time is just the RC time constant of the metal-insulator-metal sandwich, R being the zero-bias resistance resulting from the tunneling mechanism, and C being the capacitance of the structure. If we plot the log of the RC time constant as a function of insulator thickness, we should obtain a straight line whose slope is twice the average value of k encountered on the tunneling path, and whose intercept is given by a group of fundamental constants that can be found in any detailed treatment on the subject.

One straightforward way to evaluate k as a function of energy for a given material is to make structures with different barrier energies, vary their thickness, and plot the data in this way. Although this approach is straightforward in principle, it is difficult in practice because of the limited number of metal-insulator interfaces suitable for study for technical reasons. However, one can choose certain metal-insulator systems and make such plots to obtain information on the average k along the tunneling path for a particular pair of metals involving particular values of the two barrier energies.

The results of this procedure applied to gallium selenide samples [5] are shown in Fig. 15. Notice that in fact an excellent straight line is obtained, indicating that tunneling is the dominant current-flow mechanism. The intercept is within a factor of 2 of that calculated from the fundamental constants measured earlier. This is the first and most severe test of any tunneling experiment.

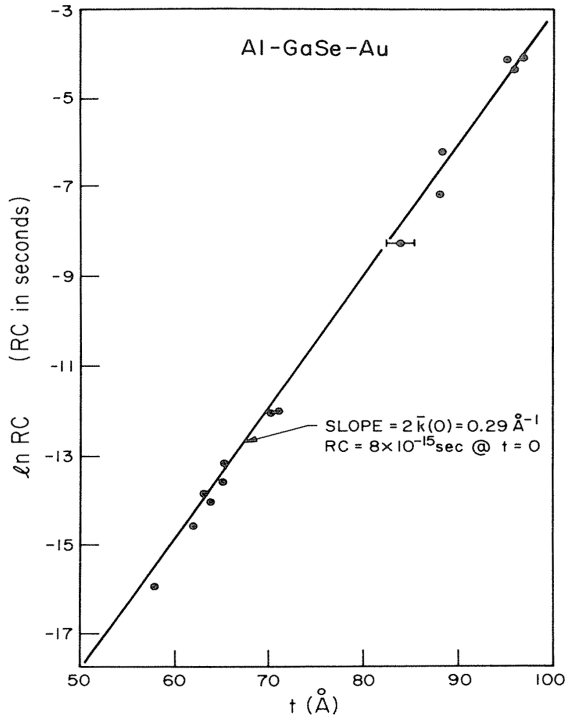

Figure 15: Dependence of the tunneling probability for samples shown in Fig. 10 on the thickness of the gallium selenide layer. The slope of this plot is a direct measure of k.

6 The Voltage Dependence of the Tunneling Current

If a voltage is applied to the tunneling sample, the Fermi level of one metal will be displaced relative to that in the other metal, and tunneling can take place from all allowed states in the negative metal into the opposite empty states in the positive metal; that is, in the entire energy range between the Fermi levels of the two metals. Thus, a calculation of the tunneling current involves determining the average k for each energy between the two Fermi levels, calculating the contribution of this energy to the tunneling current, and integrating the result over the energies between the Fermi levels. (This analysis assumes that the temperature is low enough for thermally-excited electrons to contribute negligibly to the current.) This rather complex procedure can be carried out only if the details of the dependence of k on energy are known. Since in general this dependence is not known, we are faced with the problem of determining k as a function of energy before proceeding. One approach is to use the thickness dependence of structures with different barrier energies and different applied biases. Another is to notice that the dependence of k on energy is necessary to determine the current-voltage relationship for any single tunneling sample. Both approaches have been successfully used.

Typical current-voltage characteristics for gallium selenide samples of various thicknesses are shown in Fig. 16. The vertical displacement between curves for samples of different thickness is due to the exponential dependence of the wave function on sample thickness, the same effect which gave rise to the exponential plot of Fig. 15. The current for any given sample increases in a generally exponential way with the bias applied to the sample. As already mentioned, the reason for this increase is that, as more bias is applied to the sample, the tunneling paths for electrons, at one or the other Fermi level (or perhaps both), are brought closer to the band edges where the value of k is smaller, and hence the average value of k for these tunneling paths is decreased and the current is increased. The curve in the forward and reverse direction for any given sample, together with the knowledge of the barrier energies, is sufficient to

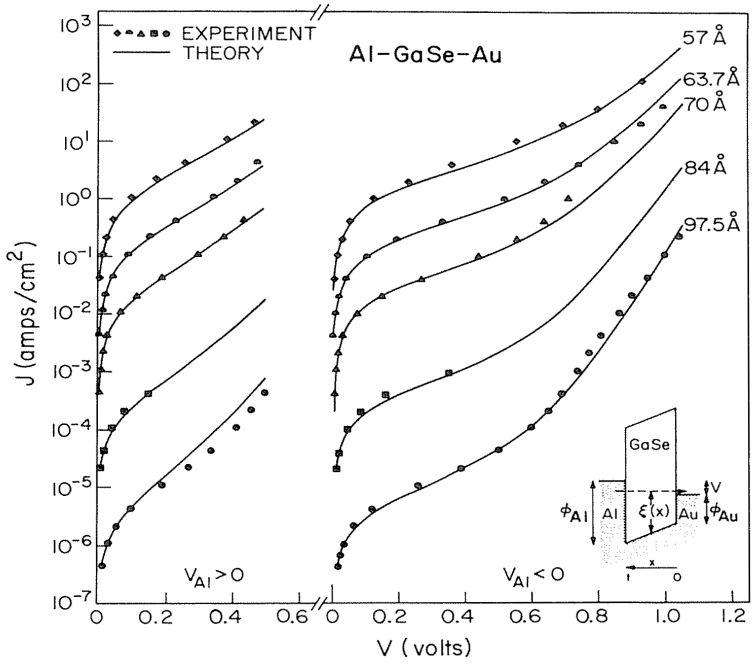

Figure 16: Current-voltage characteristics of Au-GaSe-Al structures of various thickness. Vertical displacement of the curves is due to change in thickness; increase in current with applied bias is due to the effect shown in Fig. 14; that is, change in the average k.

determine the k versus E relationship for the dielectric. Because of the integral nature of the relationship, it is necessary to unwind the dependence by numerical iteration. Conceptually, the underlying process is straightforward. It consists of taking a trial solution for the k versus E relationship, calculating the current as a function of voltage, noticing the difference between the calculated and experimental curve, and using this to adjust the k versus E relationship until the process converges.

The result of such a calculation done for gold-gallium selenide-aluminum structures is shown in Fig. 17. Notice that although the general form of the curve is similar to that of Fig. 13, there is structure that would not have been predicted by any simple approximation, and therefore it is necessary to do an experiment to determine the exact relationship. Once the relationship is known, however, there are no longer any adjustable parameters, and the current can be calculated as a function of voltage for any sample thickness and any combination of electrode materials. The results of such a calculation are shown as the solid lines in Fig. 16. Notice the excellent agreement between theory and experiment over the rather wide range of current density and thickness involved. The results indicate a high order of confidence that the theory is, in fact, representative of the actual physical process.

Since the k versus E relationship was derived from one of the curves taken on a gold-gallium selenide-aluminum structure and currents were calculated only for structures involving the same two metals, it might be thought that what we have done is construct a model that is adequate for these two particular barrier energies only, and not really characteristic of the dielectric itself. In order to dispel this fear, we must repeat the calculation for a different set of barrier energies (which result in a different tunneling path for any given applied voltage) and compare the results with experiment. This has been done for copper-gallium selenide-gold samples and is shown in Fig. 18. Notice once more the excellent agreement between theory and experiment.

The result of this study has led us to several conclusions:

- The simple theory of electron tunneling through a forbidden gap is adequate to explain with

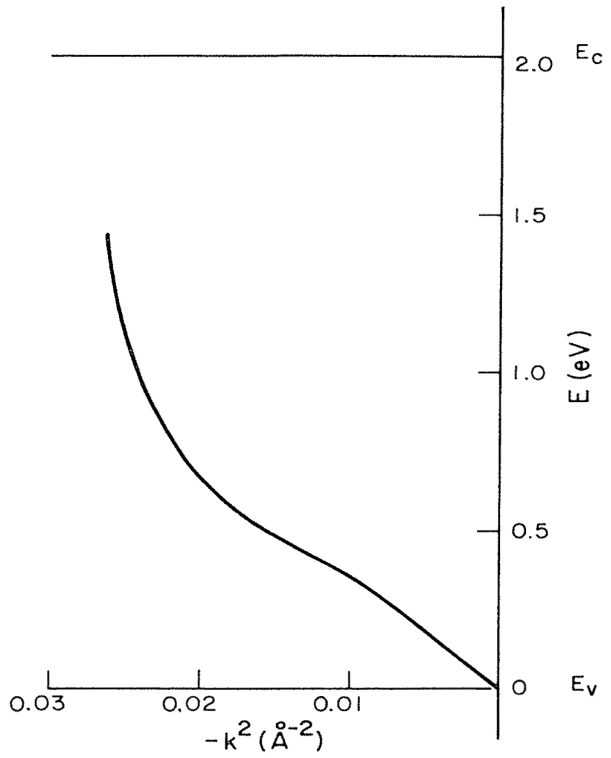

Figure 17: Energy versus k relationship for the forbidden gap of gallium selenide.

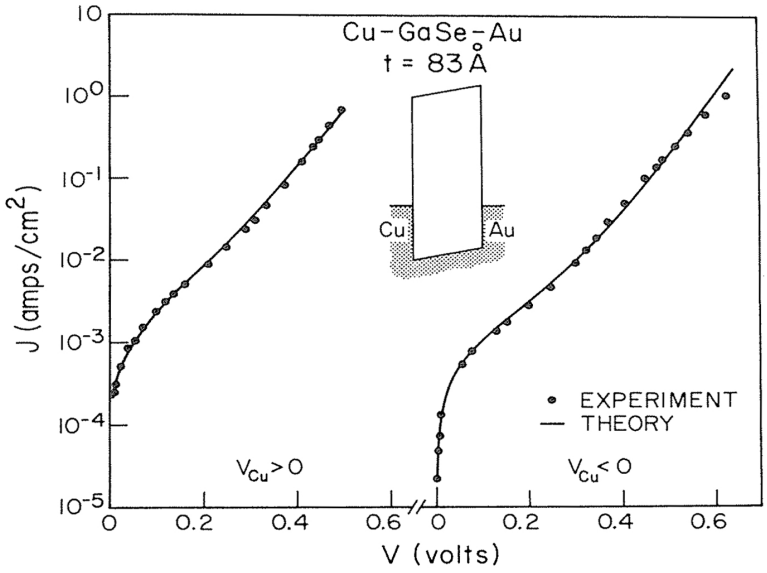

Figure 18: Theoretical and experimental current-voltage characteristics of a Au-GaSe-Cu sample, obtained by using the k versus E relationship of Fig. 17. This experiment conclusively demonstrates the internal consistency of the model.

reasonable precision experimental data taken on well-controlled and well-characterized dielectric films.

- Deriving the k versus E relationship for a dielectric can give new insight into the structure and

nature of the forbidden gap[2].

- The ability to vary independently the energy and thickness of the tunneling samples allows a high degree of overdetermination in the system, and thus the self-consistency of the results can be checked in a number of important ways.

7 High-Field Tunneling

Tunneling can occur in any situation where filled states and empty states at the same energy are separated by a forbidden region that is sufficiently thin. Even when a vacuum or dielectric film is itself much too thick for direct electrode-to-electrode tunneling to take place, a very large applied bias will result in a high electric field F:

$$F = \frac{V}{t}. \tag{8}$$

Near the electrode the vacuum level (or conduction band) will be very steep, as shown in Fig. 19, and tunneling can take place from the Fermi level of the electrode to allowed states in the vacuum (or dielectric). This process was first considered in detail by Fowler and Nordheim and bears their name.

For any electric field, electrons tunnel from the metal Fermi level to the vacuum level, the tunneling path being independent of applied bias. For this reason, the average k does not depend on bias voltage, and the form of the current-voltage characteristics may be realized immediately from Fig. 19. The distance

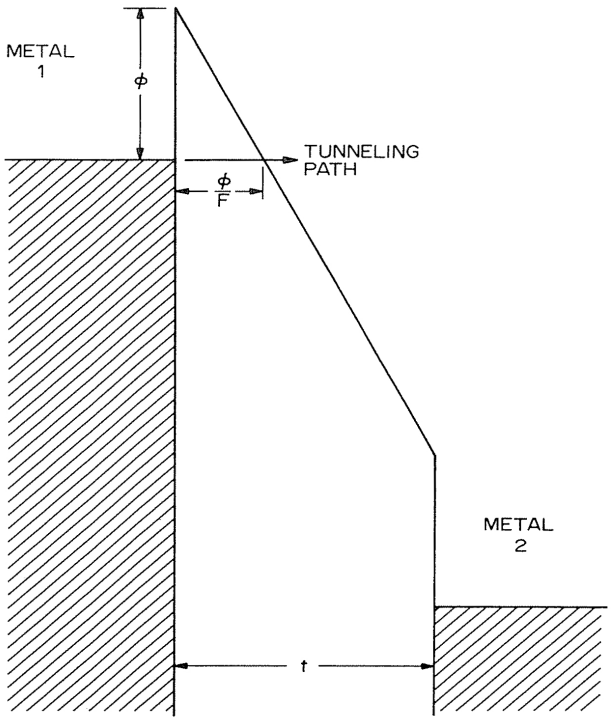

Figure 19: Energy diagram of thick metal-insulator-metal structure under high applied bias. The tunneling path carries electrons from the metal into states in the vacuum or dielectric conduction band. Note that the tunneling distance is ϕ/F.

[2]Similar experiments have been done on Schottky barriers on semiconductor materials originally by Padovani and Stratton [6] (see also Refs. [7, 8])

that an electron at the Fermi level must tunnel is $d = \phi/F$. Hence, the tunneling probability is

$$P \propto \exp\left(-\frac{2k\phi}{F}\right). \tag{9}$$

Electrons with energies below the Fermi level must tunnel further and hence make smaller contributions to the current. For this reason, the current increases essentially as Eq. 9 with some slowly varying pre-exponential factors.

Data taken by Lenzlinger and Snow [9] on a thin film of silica are shown in Fig. 20, where log J has been plotted as a function of $\frac{1}{F}$ as indicated by Eq. 9. Note that a straight line is obtained over five orders of

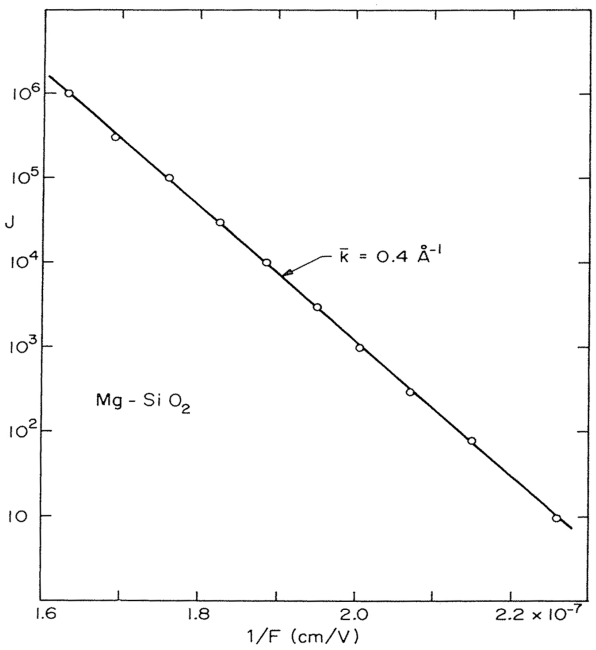

Figure 20: Fowler-Nordheim plot of the current-voltage characteristics of silica on magnesium. Although the pre-exponential factors are assumed to be constant in this simplified analysis, the results are essentially identical with those obtained in a more detailed treatment [9]. The ordinate scale J is expressed relative to those values at the lowest field, F.

magnitude in current. From the slope of this line, the average k in silica is 0.4 $\mathring{A}^{-1}$ over the energy range involved.

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